New CP phase of $B_s - \bar{B}_s$ mixing on T violation in $B_{d(s)} \to K^*(\phi)\ell^+\ell^-$

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(Dated: November 5, 2008)

Abstract

A large CP-violating phase uncovered recently by CDF and DØ collaborations in the time-dependent CP asymmetry (CPA) of the $B_s \to J/\Psi\phi$ decay clearly indicates that a non-Cabibbo-Kobayashi-Maskawa (CKM) phase has to be brought into the $b \to s$ transition. We find that the model with $SU(2)_L$ singlet exotic quarks can not only provide the new phase induced from the Z-mediated flavor changing neutral current (FCNC) at tree level, but also strongly relate the $B_s - \bar{B}_s$ mixing, $B_q \to V_q\ell^+\ell^-$ ($V_{d[s]} = K^*[\phi]$) and $B_s \to \mu^+\mu^-$ together. In particular, we show that the new CP phase can be unambiguously exposed by the large statistical significances of T violating observables in $B_q \to V_q\ell^+\ell^-$, while the branching ratio of $B_s \to \mu^+\mu^-$ can be enhanced to be $O(10^{-8})$.

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CP violation (CPV) has been one of the most mysterious phenomena in high energy physics since it was discovered in the K system [1]. At B factories, BABAR and BELLE have observed both the mixing-induced time-dependent CP asymmetry (CPA) in the B_d oscillation through the golden mode of $B \to J/\Psi K_S$ and the direct CPAs in exclusive $B \to \pi\pi$ and $B \to \pi K$ decays [2], where the former is dictated by the $b \to d$ transition while the latter $b \to s$. Although three generations of the standard model (SM) can provide a unique CP violating phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [3] to interpret the observed CPAs, it does not provide a solution to understand the matter-antimatter asymmetry in the Universe and it does not stop people to search for a new CPV source.

Nevertheless, it is very difficult to unfold a new CPV phase in the direct CPAs of the nonleptonic exclusive decays due to the inevitable large uncertainty of nonperturbative QCD effects. Hence, the best environment to look for the new phase is that the QCD effects are less involved while the SM contributions are highly suppressed. Now, the dawn to see the new effects could be in the B_s system. By the B_s production in Tevatron Run II, besides CDF and $D\emptyset$ observations on the B_s oscillation of $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1} [4] and $\Delta m_s = 18.56 \pm 0.87$ ps^{-1} [5], respectively, and the large direct CPA of 0.39 ± 0.17 for $B_s \to K^- \pi^+$ [6], an unexpected large CPV phase has been detected in the mixing-induced CPA for $B_s \to J/\Psi\phi$.

To explain the new phase, we write the transition matrix element for $\bar{B}_s \to B_s$ as

$$M_{12}^{s} \;=\; A_{12}^{\rm SM} e^{-2i\beta_s} + A_{12}^{\rm NP} e^{2i(\theta_s^{\rm NP} - \beta_s)} \tag{1}$$

where $\beta_s \equiv arg(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*})$ is the CPV phase in the SM and θ_s^{NP} is the new CPV phase in some extension of the SM. Here, the convention has been chosen to be the same as that in Ref. [7]. Due to $\Delta\Gamma_s \ll \Delta m_s$ in the B-system [8], the time-dependent CPA could be simplified to be

$$\begin{aligned} -\,S_{J/\Psi\phi} \;&\simeq\; {\rm Im}\left(\sqrt{\frac{M_{12}^{s*}}{M_{12}^{s}}}\right) = \sin(2\beta_s - \phi_s^{\rm NP})\,, \\ \phi_s^{NP} \;&=\; \arctan\left(\frac{r\sin 2\theta_s^{\rm NP}}{1 - r\cos 2\theta_s^{\rm NP}}\right) \end{aligned} \tag{2}$$

with $r = A_{12}^{NP}/A_{12}^{\rm SM}$. By adopting Wolfenstein parametrization [9] of the CKM matrix up to $O(\lambda^4)$, in which $V_{tb} = 1 - A^2\lambda^4/2$, $V_{ts} = -A\lambda^2 + 1/2A\lambda^4\,(1 - 2(\rho + i\eta))$, $V_{cb} = A\lambda^2$ and

$V_{cs} = 1 - \lambda^2/2 - 1/8\lambda^4(1+4A^2)$ [10], one can easily find

$$\beta_s \approx \lambda^2 \eta \approx 0.019\,, \tag{3}$$

where $\lambda = 0.2272$ and $\eta = 0.359$ [8] have been used. Clearly, the mixing-induced CPA of B_s in the SM is only few percent. Astonishingly, the nonvanished CP phase measured by CDF [11] and DØ [12] is

$$\phi_s = 2\beta_s - \phi_s^{NP} = \begin{cases} [0.24,\, 1.36] \cup [1.78,\, 2.82] & \text{(CDF)} \\ 0.57^{+0.30+0.02}_{-0.24-0.07} & \text{(DØ)} \end{cases} \tag{4}$$

at the 68% confidence level (CL), while the allowed range at the 90% CL by DØ is given to be $\phi_s \in [-0.06,\, 1.20]$. Recently, the UTfit collaboration has combined all available information in the B_s system and concluded that the CPV phase of the B_s mixing amplitude deviates more than 3σ from the SM value [7]. To explain the large CPV phase in the $b \to s$ transition, several new physics models have been proposed [13]. In this paper, we explore the effects of the large phase in the decays of $B_q \to V_q \ell^+\ell^-$ ($V_{d(s)} = K^*(\phi)$), corresponding to $b \to s\ell^+\ell^-$ at the quark level. In particular, we will show that the large CPV phase can be directly probed by measuring T-odd observables in the decays.

To comprehend the beauty of using T violation to probe the CPV phase, we briefly summarize the characters of CP-odd and T-odd observables. In a decay process, the direct CPA or CP-odd observable is defined by $\mathcal{A}_{CP} \equiv (\bar{\Gamma} - \Gamma)/(\bar{\Gamma} + \Gamma)$, where Γ ($\bar{\Gamma}$) is the partial decay rate of the (CP-conjugate) process. As a result, $\mathcal{A}_{CP} \propto \sin\theta_w \sin\theta_{st}$ with $\theta_{w(st)}$ being the weak (strong) phase. Clearly, to have a nonvanished CPA, both phases are needed. The efficiency on the CPA is mainly dictated by the uncertain calculations of the strong phase. Another way to probe the CPV phase is through the spin-momentum triple correlation, such as $\vec{s} \cdot (\vec{p}_i \times \vec{p}_j)$ [14, 15, 16] for a three-body decay, where $\vec{s}$ is the spin carried by one of outgoing particles and $\vec{p}_i$ and $\vec{p}_j$ denote any two independent momenta. The triple correlation is a T-odd observable since it changes sign under the time reversal (T) transformation of $t \to -t$. We note that the T transformation defined here is different from the real time-reversal transformation which also contains the interchange of initial and final states. By the CPT invariant theorem, T violation (TV) implies CPV. Therefore, the study of the T-odd observable can help us to understand the origin of CPV. Intriguingly, the T-odd triple correlation is proportional to $\sin(\theta_w + \theta_{st})$, which indicates that the strong

phase is not necessary to achieve a nonzero T-odd observable. It has been shown in Ref. [16] that T-violating effects in the exclusive $b \to s\ell^+\ell^-$ processes are sensitive to new physics with small QCD uncertainties, which could provide a good place to directly observe the new phase revealed by CDF and DØ.

The transition amplitudes for $B_q \to V_q\ell^+\ell^-$ ($\ell = e, \mu$) are given by [16, 17]

$$\begin{aligned}
\mathcal{M}_{V_q}^{(\lambda)} &= -\frac{G_F\alpha\lambda_t}{2\sqrt{2}\pi}\left\{\mathcal{M}_{1\mu}^{(\lambda)}L^\mu + \mathcal{M}_{2\mu}^{(\lambda)}L^{5\mu}\right\}, \\
\mathcal{M}_{a\mu}^{(\lambda)} &= if_1\varepsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}(\lambda)P^\alpha q^\beta + f_2\epsilon_\mu^*(\lambda) + f_3\epsilon^*\cdot qP_\mu\,,
\end{aligned}$$

where $\lambda_t = V_{tb}V_{ts}^*$, $L_\mu = \bar\ell\gamma_\mu\ell$, $L_\mu^5 = \bar\ell\gamma_\mu\gamma_5\ell$, $P = p_B + p_V$, $q = p_B - p_V$, $a = 1\,(2)$ while $f_i = h_i$ (g_i) and

$$\begin{aligned}
h_1 &= \frac{C_9^{\rm eff}V}{m_B+m_V} + \frac{2m_b}{q^2}C_7T_1\,, \\
h_2 &= -\frac{1}{2}(m_B+m_V)C_9^{\rm eff}A_1 - \frac{1}{2}\frac{2m_b}{q^2}P\cdot qC_7T_2\,, \\
h_3 &= \frac{C_9^{\rm eff}A_2}{m_B+m_V} + \frac{2m_b}{q^2}C_7\Big(T_2(q^2) + \frac{q^2}{P\cdot q}T_3\Big)\,, \\
g_i &= h_i|_{C_9^{\rm eff}\to C_{10},C_7=0}\,, \quad (i=1,2,3)\,.
\end{aligned} \tag{5}$$

Here, $m_B(m_V) \equiv m_{B_q}(m_{V_q})$, $C_9^{\rm eff}$, C_7 and C_{10} are the Wilson coefficients [18] and the definitions of the form factors in Eq. (5) can be found in Ref. [16]. Furthermore, to obtain T-odd terms, the polarizations of V_q should be kept in the averaged squared-amplitude. To achieve the requirement, we have to consider the decay chain $B_q \to V_q(\to P_1P_2)\ell^+\ell^-$ in which P_1P_2 is $K\pi(KK)$ as $V_q = K^*(\phi)$. Consequently, the differential decay rate associated with these terms is given by

$$\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_K d\cos\theta_\ell d\phi dq^2} = \frac{3\alpha^2G_F^2\,|\lambda_t|^2\,|\vec{p}|}{2^{14}\pi^6m_B^2} \\
&\times\{4\cos^2\theta_K\sin^2\theta_\ell\sum_{i=1,2}|\mathcal{M}_i^0|^2 + \sin^2\theta_K(1+\cos^2\theta_\ell) \\
&\sum_{i=1,2}\left(|\mathcal{M}_i^+|^2 + |\mathcal{M}_i^-|^2\right) - \sin 2\theta_K\sin 2\theta_\ell\sin\phi \\
&\sum_{i=1,2}Im\left(\mathcal{M}_i^+ - \mathcal{M}_i^-\right)\mathcal{M}_i^{0*} - 2\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \\
&\sum_{i=1,2}Im\left(\mathcal{M}_i^+\mathcal{M}_i^{-*}\right) + 2\sin 2\theta_K\sin\theta_\ell\sin\phi(Im\mathcal{M}_1^0 \\
&(\mathcal{M}_2^{+*} + \mathcal{M}_2^{-*}) - Im(\mathcal{M}_1^+ + \mathcal{M}_1^-)\mathcal{M}_2^{0*}) + \cdots]\}\,,
\end{aligned} \tag{6}$$

where $\theta_\ell(\theta_K)$ is the polar angle of the lepton (K-meson) in the q^2 (V_q) rest frame, $|\vec{p}| = [((m_B^2+m_V^2-q^2)/(2m_B))^2-m_V^2]^{1/2}$ and $\mathcal{M}_i^0$ and $\mathcal{M}_i^\pm$ denote the longitudinal and transverse polarizations of V_q with their explicit expressions being

$$\begin{aligned}
\mathcal{M}_a^0 &= \sqrt{q^2}\left(\frac{E_V}{m_V}f_2 + 2\sqrt{q^2}\frac{|\vec{p}_V|^2}{m_V}f_3\right), \\
\mathcal{M}_a^\pm &= \sqrt{q^2}\left(\pm 2\,|\vec{p}_V|\,\sqrt{q^2}f_1 + f_2\right),
\end{aligned} \tag{7}$$

respectively. To shorten the expressions, we have only presented the relevant pieces in Eq. (6), where the three imaginary terms denote the T-violating effects. The whole expression for differential decay rate could refer to Refs. [16, 19].

From Eqs. (5), (6) and (7), it is easy to show that the large contributions to the T-violating effects arise from $Im\mathcal{M}_1^0(\mathcal{M}_2^{+*}+\mathcal{M}_2^{-*}) - Im(\mathcal{M}_1^+ + \mathcal{M}_1^-)\mathcal{M}_2^{0*}$. To explore the effects, we examine the T-odd observable, defined by $\langle\mathcal{O}_T\rangle = \int \mathcal{O}_T d\Gamma$ where $\mathcal{O}_T$ is a T-odd five-momentum correlation, given by

$$\mathcal{O}_T = \frac{\vec{p}_B\cdot\vec{p}_K}{|\vec{p}_B|\,|\vec{p}_K|}\frac{\vec{p}_B\cdot(\vec{p}_K\times\vec{p}_{\ell^+})}{|\vec{p}_B|\,|\vec{p}_K|\,\omega_{\ell^+}} \tag{8}$$

with $\omega_{\ell^+} = q\cdot p_{\ell^+}/\sqrt{q^2}$. In the V_q rest frame, we note that $\mathcal{O}_T = \cos\theta_K\sin\theta_K\sin\theta_\ell\sin\phi$. To signal the nonvanished CPV phase, we employ the statistical significance of the observable, defined by

$$\varepsilon_T(q^2) = \frac{\int \mathcal{O}_T d\Gamma}{\sqrt{(\int d\Gamma)(\int \mathcal{O}_T^2 d\Gamma)}}\,. \tag{9}$$

Integrating all relevant angles in Eq. (9), we obtain

$$\begin{aligned}
\varepsilon_T(q^2) &\simeq \frac{0.76}{\sqrt{\mathcal{D}_1\mathcal{D}_2}}[Im\mathcal{M}_1^0(\mathcal{M}_2^{+*}+\mathcal{M}_2^{-*}) - \\
&\quad Im(\mathcal{M}_1^+ + \mathcal{M}_1^-)\mathcal{M}_2^{0*}]\,, \\
\mathcal{D}_a &= \sum_{i=1,2}\left[\left|\mathcal{M}_i^0\right|^2 + \frac{1}{a}\left(\left|\mathcal{M}_i^+\right|^2 + \left|\mathcal{M}_i^-\right|^2\right)\right].
\end{aligned} \tag{10}$$

To observe the effect at $n\sigma$ level, the required number of B mesons is $N_B = n^2/(Br\cdot\varepsilon_T^2)$.

We now use the clue of the current data to illustrate our model-independent analysis. Although the principle of the minimal flavor violation (MFV) [20] could be as a dogma to rule the new source of CPV [21], to focus on the criterion of the minimal extension of the SM, we employ the vector-like-quark model (VQM), in which the vector-like quarks (VQs) are $SU(2)_L$ singlet exotic quarks, as the ones naturally realized in E_6 models [22]. Explicitly,

we include $SU(2)_L$ singlet VQs in the SM, where the right-handed component is the same as the right-handed down-quark. Since the singlet quarks do not couple to W-bosons directly, one of the fascinating characters of the model is that the corresponding CKM matrix is not a unitary matrix. By introducing flavor mixing matrices to diagonalize the 4×4 down-type quark mass matrix, we will display that the model interestingly leads to Z-mediated flavor changing neutral currents (FCNCs) at tree level [23], which clearly have significant impacts on the $B_s - \bar{B}_s$ mixing, $B_q \to V_q \ell^+ \ell^-$ and $B_s \to \mu^+ \mu^-$ processes. We note that the non-unitary CKM matrix could result in new contributions to the processes from box and penguin diagrams. However, to simply illustrate the new phase, only the Z-mediated effects at tree level are considered here, while those from the box and penguin diagrams could be referred to Ref. [24].

In the mass eigenstates, the coupling of the Z-boson to fermions is written by

$$\begin{aligned} \mathcal{L}_Z &= -\frac{g c_L^f}{2\cos\theta_W} \bar{F} \gamma^\mu \left(V_F^L X_F V_F^{L\dagger} \right) P_L F Z_\mu \,, \\ X_Q &= \left[\begin{array}{c|c} \mathbb{1}_{3\times 3} & \mathbf{0}_{3\times 1} \\ \hline \mathbf{0}_{1\times 3} & \xi_Q \end{array} \right] , \quad X_\ell = \mathbb{1}_{3\times 3} \,, \end{aligned} \tag{11}$$

where g is the coupling constant of $SU(2)_L$, θ_W is the Weinberg's angle, $P_{R(L)} = (1 \pm \gamma_5)/2$, $F^T = (q_1, q_2, q_3, q_4)$ and (e, μ, τ) represent quarks (Qs) and leptons (ℓs), c_L^f is defined as $c_L^f = c_V^f + c_A^f$ with

$$c_V^f = T_f^3 - 2\sin^2\theta_W Q_f \,, \quad c_A^f = T_f^3 \tag{12}$$

in which T_f^3 and Q_f are the third component of the weak isospin and the electric charge of the particle, respectively, and $\xi_f = -2\sin^2\theta_W Q_f / c_L^f$. Here, as the quantum number of the new right-handed VQ is the same as the right-handed down-quark, the tree FNCNs only occur in the left-handed quarks. Accordingly, the interaction for b-s-Z is given by

$$\mathcal{L}_{b\to s} = \frac{g c_L^D \lambda_{23}}{2\cos\theta_W} \bar{s} \gamma^\mu P_L b Z_\mu + H.c. \tag{13}$$

with $\lambda_{23} = (1 - \xi_D)(V_D^L)_{24} (V_D^L)^*_{34} \equiv |\lambda_{23}| \exp[i(\theta_s^{\rm NP} - \beta_s)]$. By Eqs. (1) and (13), the transition matrix element for the $\Delta B = 2$ process is obtained as

$$A_{12}^{\rm NP} = \frac{G_F \left(\lambda_{23}\right)^2}{3\sqrt{2}} m_{B_s} f_{B_s}^2 \hat{B}_s \,. \tag{14}$$

As a result, the $B_s - \bar{B}_s$ mixing in the VQM is

$$\Delta m_s = \Delta m_s^{\rm SM} \left(1 + 2r\cos\theta_s^{\rm NP} + |r|^2\right)^{1/2} . \tag{15}$$

From the above equation, it is clear that a large new CPV phase can have a significant influence on the $B_s - \bar{B}_s$ mixing. By combining the SM and Z-mediated FCNC, the branching ratio (BR) of $B_s \to \mu^+\mu^-$ is found to be

$$\mathcal{B}_{\ell^+\ell^-} = \tau_{B_s} \frac{G_F^2}{16\pi} m_{B_s} f_{B_s}^2 m_\ell^2 \left(1 - \frac{4m_\ell^2}{m_{B_s}^2}\right)^{1/2} \left(|\Re|^2 + |\Im|^2\right),$$

$$\begin{aligned} \Re &= -\frac{|\lambda_t|\alpha}{\pi \sin^2\theta_W} Y(x_t) + |\lambda_{23}| c_L^D \cos\theta_s^{\rm NP}, \\ \Im &= |\lambda_{23}| c_L^D \sin\theta_s^{\rm NP}. \end{aligned} \tag{16}$$

We can also obtain the effects of the Z-mediated FCNCs on $B_q \to V_q \ell^+\ell^-$ decays by utilizing the replacement:

$$\begin{aligned} C_9^{\rm eff}[V, A_{1(2)}] &\to \left(C_9^{\rm eff} + \frac{4\lambda_{23}}{\alpha\lambda_t} c_L^D c_V^\ell\right)[V, A_{1(2)}], \\ C_{10}[V, A_{1(2)}] &\to \left(C_{10} - \frac{4\lambda_{23}}{\alpha\lambda_t} c_L^D c_A^\ell\right)[V, A_{1(2)}]. \end{aligned} \tag{17}$$

We note that in the following numerical analysis we will concentrate on $B_d \to K^* \ell^+\ell^-$ as they have already been observed. However, the same discussions can be easily applied to $B_s \to \phi \ell^+\ell^-$.

In the Z-mediated $b \to s$ transition, the magnitude $|\lambda_{23}|$ and the phase $\theta_s^{\rm NP}$ can be determined by the observed B_s mixing and BR of $B_d \to K^{*0}\mu^+\mu^-$. We adopt the average value of $\Delta m_s = 18.17 \pm 0.86$ ps^{-1} [4, 5] and $\mathcal{B}(B_d \to K^{*0}\mu^+\mu^-) = (1.22^{+0.38}_{-0.32}) \times 10^{-6}$ [8] as the inputs, while the SM results are taken to be $\Delta m_s^{\rm SM} = 19.3 \pm 6.7$ ps^{-1} [25], $\mathcal{B}(B_d \to K^{*0}\mu^+\mu^-)_{\rm SM} = 1.3 \times 10^{-6}$ [26] and $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} \approx 0.33 \times 10^{-8}$ with $V_{ts} = -0.04$ and $f_{B_s} = 0.23$ GeV. In order to reveal the strong correlations among Δm_s, $\mathcal{B}(B_d \to K^{*0}\ell^+\ell^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ influenced by the same parameters, we present $\mathcal{B}(B_s \to \mu^+\mu^-)$ versus Δm_s [$\mathcal{B}(B_d \to K^{*0}\ell^+\ell^-)$] in Fig. 1(a)[(b)]. From the figures, we see clearly that the Z-mediated effects could enhance the BR of $B_s \to \mu^+\mu^-$ to be $O(10^{-8})$, which is close to the current upper limit of 4.7×10^{-8} [27]. With the constrained values of λ_{23} and $\theta_s^{\rm NP}$, in Fig. 2(a) we show the allowed ϕ_s given by Eq. (4). It is wroth mentioning that $\mathcal{B}(B_s \to K^{*0}\ell^+\ell^-)$ excludes ϕ_s larger than 0.2 rad. Furthermore, we present the contributions of the new CP

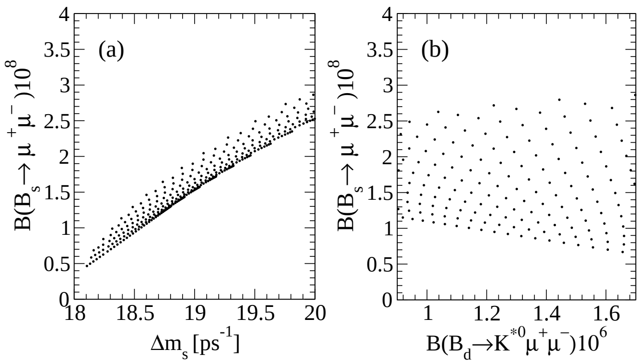

FIG. 1: (a)[(b)] $\mathcal{B}(B_s \to \mu^+\mu^-)$ versus Δm_s [$\mathcal{B}(B_d \to K^{*0}\ell^+\ell^-)$].

violating source to the T-odd observable of Eq. (10) in Fig. 2(b). Intriguingly, the new phase can lead to a large statistical significance of the T-odd observable in $B_q \to V_q \ell^+\ell^-$.

In summary, motivated by the large CP phase found by CDF and DØ in the $B_s - \bar{B}_s$ mixing, we have investigated the $SU(2)_L$ singlet VQM. This model can not only provide the large phase through the Z-mediated FCNCs at tree level, but also strongly relate Δm_s, $B_q \to V_q \ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ processes. In particular, we have shown that the new CP phase can be unambiguously exposed by the large statistical significances of the T-violating observables in $B_q \to V_q \ell^+\ell^-$ ($V_q = K^*$, ϕ). In addition, we have found that $\mathcal{B}(B_s \to \mu^+\mu^-)$ can be enhanced as large as $O(10^{-8})$. Finally, we remark that the T-violating effects in $B_q \to V_q \ell^+\ell^-$ as well as the result on $\mathcal{B}(B_s \to \mu^+\mu^-)$ are accessible at future super-B factories, such as the SuperKEKB [28] and LHCb [29]. For example, 4400 events/year for $B \to K^* \ell^+\ell^-$ decays will be produced at the LHCb, corresponding to the accuracy of the T-odd observable being around percent level.

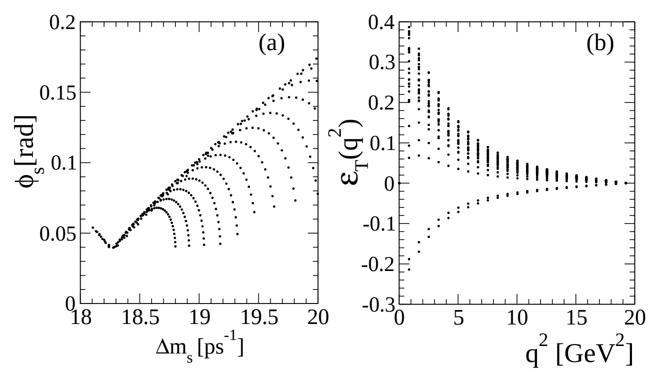

FIG. 2: (a) Correlation of $\phi_s = 2\beta_s - \phi_s^{\rm NP}$ and Δm_s. (b) Statistical significance ε_T of $B_d \to K^{*0}\mu^+\mu^-$ as a function of q^2.

Acknowledgments

This work is supported in part by the National Science Council of R.O.C. under Grant #s: NSC 97-2112-M-006 -001-MY3 and NSC-95-2112-M-007-059-MY3.

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